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Using water treatment sludge to Improve Geotechnical Engineering Properties of Soils: A Review

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ABSTRACT

Water treatment sludge (WTS) is a byproduct generated during wastewater treatment. In recent years, researchers have explored the potential of using WTS as a soil stabilizer to improve the geotechnical properties of soils. This review will examine the current knowledge on using WTS for this purpose. The organic matter content of WTS is usually high and can range from 30% to 60%. The high organic matter content makes WTS a potential source of nutrients for plants, and it can also enhance soil structure and water retention. Another important consideration is the environmental impact of using WTS. The use of WTS can be an eco-friendly alternative to chemical stabilizers, which can have adverse effects on the environment. However, there are concerns about the potential for heavy metal contamination in WTS. To mitigate this risk, it is recommended to thoroughly test WTS before using it as a soil stabilizer. Finally, using WTS as a soil stabilizer can potentially improve the geotechnical properties of soils. However, it is essential to consider factors such as the type and dosage of WTS, the soil type, and the environmental impact before using it. Further research is needed to explore the potential of using WTS in different soil types and environmental conditions.

1. Introduction

Sludge is created in large quantities during wastewater treatment and must be disposed of. Using sludge on agricultural land, essential components such as organic matter, N, P, and other plant nutrients may be recycled. Heavy metals tend to accumulate in the formed sludge, and heavy metal levels rise due to the physical-chemical processes utilized in wastewater treatment. The production of sludge from water treatment plants (WTP) in IRAQ [1] is predicted to exceed 78 million tons. This output is more than that of other nations, according to [2], but like other estimates in nations like the Netherlands and Japan [3]. There are few publicly available statistics on managing drinking sludge in Iraq and most other countries [1,4].

The remainder of this waste is dumped into rivers directly downstream of the place of usage, with some of it ending up in landfills [5]. The sludge composition is influenced by the treatment chemicals employed and the input water quality [6]. This waste comprises both organic and inorganic components [7], primarily Fe, Al, Mn, and Cu [8], as well as bacteria [10] and polycyclic aromatic hydrocarbons [9]. Ferric or aluminum

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oxide-based coagulants are often used in water station facilities in Brazil [11], leading to the sludge's popular names of ferric sludge and aluminum sludge. In Brazil, sludge from water treatment plants is considered a non-hazardous waste [12], and its producers should adhere to regulations that encourage reduced production, reversal, and final disposal of unrecoverable components [13].

2. Literature Review

The literature regularly discusses the reuse of "water treatment sludge" [14]. The recovery of its components [15], as well as its application as an absorbent material to treat leachate [16], organic contaminants in surface water [17], CO2 gas [18], and metal ions [19], including lead [20] and nickel ions [21], are a few examples. The manufacturing of ceramic materials, including common bricks [22], nonstructural and decorative bricks [23], cement-free geopolymers [24], and glazed tiles [25] has found success worldwide when WTS partially replaces natural soils for civil building applications. Research in Brazil has suggested WTS as a material for civil construction [26] and assessed this waste's capacity to provide a variety of products [27], including structural bricks [28].

WTS used in alkaline soils also seems theoretically viable given that it can help restore damaged mining regions by immobilizing inorganic phosphorus in poor soils [29]. Such an application boosts germination biomass, microbiological survival, and metal immobilization [30, 31]. In some cases, using WTS and soil mixes for geotechnical operations was deemed sufficient. WTS, the organic portion of municipal solid waste, and soil mixes, according to Caniani et al. (2013) [32], were suitable for landfill covers. Boscov et al. (2021) [33] elucidated that adding Brazilian WTS to the soil for landfill cover proved geotechnically viable. According to Nazir et al. (2020) [34], WTS might be utilized again if 10% of the material typically used in the sub-base course was substituted. After analyzing ferric WTS and sand soil combinations, Montalvan (2016) [35] elucidated that a 5:1 (soil: WTS) ratio may be effective in dams. Coelho et al. (2015) [36] discovered that if 10% cement is added to the mixes, WTS may be utilized to substitute natural soil as a substrate for road pavements. Using natural soil as a partial replacement in road construction is crucial for long-term advantages in this productive chain [37]. Frequently, these works employ a great number of virgin materials since aggregates and dirt from quarry sites form an important portion of the pavement frame [38].

Meeting the ever-increasing request for economic and physical resources is one of the most challenging aspects of highway pavement development [39]. Sustainable construction and clean production options for the road-building industry include the utilization of secondary (reused) materials rather than primary (pristine) materials to reduce the extraction requirement and pressure on landfills [40]. However, positive results were obtained when WTS partially substituted natural soil in road building. The following deficiencies in these studies preclude their used in Brazil: Most WTP in the country has not been representatively and comparatively analyzed because only one WTS kind and soil is present and, generally, is estimated. Sludge generation is large, continuous, and increasing, resulting in low incorporation rates and making this material unsuitable for application. Any specific law does not permit this beneficial use, so it cannot be applied. This study studied the use of aluminum and ferric coagulants WTS to replace indigenous Brazilian soils in road construction geotechnical operations partially. In this study, different regions of Brazil have different soil and sludge compositions, which must be analyzed to develop rules for allowing massive volumes of this waste to be used for beneficial purposes.

3. " Water treatment sludge" (WTS)

Water treatment sludge (WTS) is the residue left over following regular decanter and filter cleaning in water treatment plants (WTPs). The key treatment techniques utilized in a typical WTP to transform raw water into potable water include coagulation, flocculation, decantation, filtration, pH correction, disinfection, and fluoridation. Several chemicals, including chlorine, coagulants, lime, and fluorine, are introduced to the water throughout these operations. WTS forms as pollutants settle in filters and the bottom of sedimentation basins that regularly cleaned with coagulants (polymeric, ferric, and alum).

WTS represents 0.2 to 5% of all treated water [41], and global potable water demand is expected to grow by 1% annually [42]. Currently and in the future, WTS will be a considerable waste source. More than 97% of WTS is chemical compounds from the treatment process, water, and suspended solids like soil particles (sand, clay, and silt). Still, it additionally could include viruses, bacteria, algae, and organic materials. The solids content is often increased by dewatering to 20–30%, or 250–400%, in a suspension with gravimetric water content.

This practice is not permitted in countries with strict environmental regulations since it causes silting and deteriorated water quality. Sustainability problems arise with environmentally friendly alternatives, like waste disposal in sanitary landfills or sewage discharge into sewage treatment plants (STPs). STPs, which in most developing countries are insufficient, are compromised by WTS, while specialized landfills contradict the priority of reducing waste disposal on land globally. Alternatively, reuse has the potential to incorporate WTS into the circular economy and replace natural resources in a wide range of production processes.

3.1. Sustainable disposal and reuse of " water treatment sludge " (WTS)

The ISO 24512:2007 standard specifies a method for assessing water supply management by considering the proportion of reused or recycled WTS that has been used . The UN Sustainable Development Goal (6) Water and Sanitation [43] also addresses WTS sustainability. Precast concrete elements, brick, ceramic, and cement production [44-45], composting [46], phosphorous removal from residual waters [47,48], crop production [49], and forestry [50], among others; heavy metal absorption [51,52], coagulant recovery [53,54], landfill lining [55,56], and geotechnical material [57,58].

Some researchers [59,60] have explored favourable reuse/recycling options for WTS. Despite an important studies number, rarely does the literature reuse WTS . Although just a fraction of the overall mass, unique management strategies were reported by government agencies in various nations in the 2000s. These included forestry, agriculture, reclamation of land, integration in soils, enhancement of soil, and inclusion into building materials (e.g., Germany, USA, France, UK, Japan). The information on the appropriate websites, legislation, and technical reports has not been updated in recent years. WTS utilization may have been surpassed by the wastewater reuse and "water treatment sludge" like biosolids that have a wide range of applications and are significantly more abundant. This does not imply that WTS reuse doesn't occur; e.g., in Portugal, WTS is utilized as a water treatment additive, and the USEPA issued WTS reuse standards in 2011.

On the other hand, developing countries require good research to increase WTS reuse under their specific circumstances and data on the performance of current real systems. Geotechnical research on WTS and practical applications has increased in recent years, although it remains limited. The present paper explores the potential of utilizing WTS at as-collected water content in geotechnical like sanitary and industrial landfill covers and bottom liners, trench backfill, building subbases and pavement, geosynthetic-reinforced earth walls, bridge abutments , soft embankments, and soil reinforcement. Furthermore, based on experimental results, it examines the long-term feasibility of this technology, with the objective of positive waste reuse and the natural geomaterials preservation. Two methods are being considered: (1) to safeguard natural resources, part of WTS will be substituted with soils with adequate geotechnical properties; and (2) a new geomaterial is developed by combining WTS with additives, with a positive reuse objective.

3.2. The Effectiveness of Adding WTS

Due to the potential reduction of shear strength, increase in compressibility, or reduction in soil workability caused by WTS addition, the maximum WTS value was pursued in the first approach. Geotechnical properties of two sludges and two soils were examined by mixing them in various proportions. The second strategy inspected WTS-additive blends that could generate minimal undrained strength for spreading and field workability. For low-soliciting stress applications, lime and rock powder were blended individually with sludge to create a workable material. We suggest experimental changes for dealing with materials with lower shear strengths than soft clays. The scientific basis given by (Tsugawa, J.K. et al. 2019) [61] for introducing rheology into geotechnical testing is first applied to WTS. A variety of materials were developed as a result with excellent geotechnical properties. The experimental outcomes of both approaches are then compared and contrasted regarding their technical viability and social, economic, and environmental sustainability. Developing sustainable water and sanitation business models and environmental regulations remains challenging in developing countries.

This study's new methodologies and scientific contribution comprised of (1) In the absence of any prior treatment, like drying or chemical addition, reusing WTS as collected would be significantly less economic (geotechnical properties of WTS can be enhanced by air or oven drying, but they require energy, space, and time to complete); (2) It is essential to determine the multifunctional materials' geotechnical properties, as overall study targets a single application, promising materials may be discarded for geotechnical reasons distinct from those anticipated in the initial envision, a multifunctional technique may best determine reuse; and (3) in the context of sustainability, integrating geotechnical and rheological experiments is necessary to comprehend the geomaterials conduct, as well as to explore novel methods of manipulation and conveyance. The present article used the geotechnical definition of the water content (w) which can be termed as the ratio of pore water mass to dry solid mass represented as a percentage to estimate the water amount in the material. The solids content (SC) value, which is used in water-treatment literature, is defined as the percentage ratio of the dry solid mass to the bulk sludge mass, and it may be linked to the value of water content utilizing the next equation (1):

$$SC = 100/(1 + (\tfrac{w}{100}))\ \% \qquad (1)$$

The oven-drying procedure was used to determine the water content. The dry solids mass corresponds to the mass obtained after drying the test material in an oven at 1058C5 8C for 24 hours. Novak and Calkins (1975) [62], Raghu and Hsieh (1986) [63], Geuzens and Dieltjens (1991) [64], Wang et al. (1992) [65], and Lim et al. (2002) [66] reported the geotechnical features of certain alum and iron coagulant WTS materials. Wang and Tseng (1993) [67] examined alum WTS permeability.

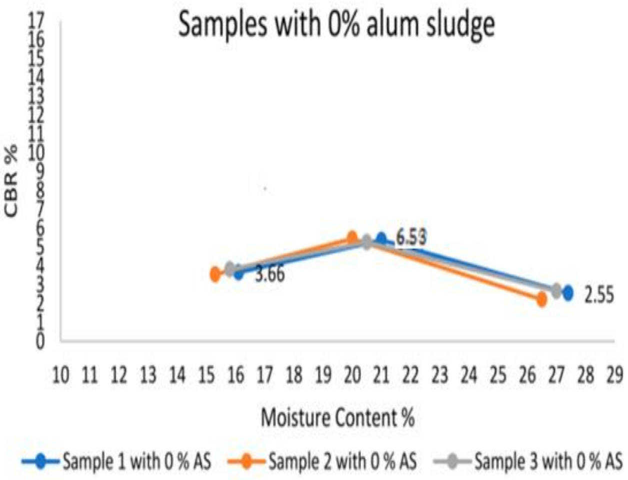
4. Natural Soils Problems

Han [68] looked at differential settlements, bearing failure, hydro compression, water seepage, instability, ground heave, liquefaction, and erosion. Table (1) can be used to depict natural soil concerns in geotechnical applications:

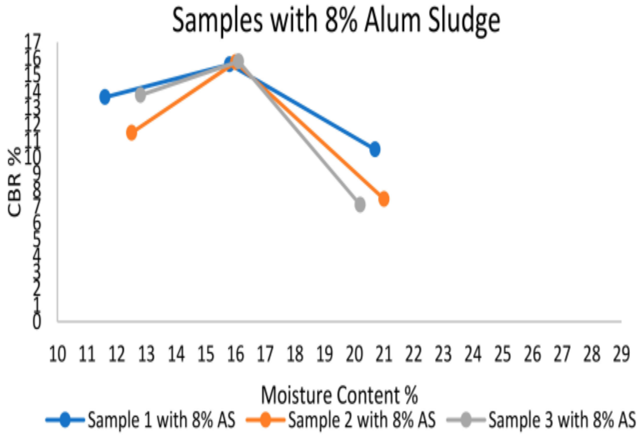
4.1. " Expansive soil "

Muhammad Aamir et al (2019) [108] researched and found that the addition of " water treatment sludge " to soil raised the soil bearing ratio greatly from 6.53 per cent to 16.86 per cent at the optimal level of an 8 per cent addition of " water treatment sludge ", as shown in Figure 1. Additionally, artificial neural networks (ANNs) were used to examine the relationship between CBR and expansive soil's physical properties, which revealed that at 8% optimum " water treatment sludge ", index of plasticity, optimum moisture content, and maximum dry density were all enhanced.

Soil is the most essential and widely available substance on the planet. It is created through the breakdown of rocks. In building areas, dirt may be employed as the cheapest construction material. Clayey soil is difficult to work with because it expands. As a result, building structures on clayey soil poses several challenges. Such soils require treatment to minimize the settlement and stability issues associated with " expansive soil " [69]. Minerals that can absorb water, such as smectite clays, can be found in " expanding soil "s. As they absorb water, they increase in size. As they absorb more water, they expand in bulk.



a) Before adding 8% sludge.



b) After adding 8% sludge.

Figure 1. Soil bearing ratio before and after adding 8% sludge.

This volume change has the potential to damage a building or other frame. Cracks in foundations, floors, and basement walls are widespread due to swollen soils. The higher levels may be damaged when there is a lot of movement in the building. When "expansive soil" dries up, it shrinks. This shrinkage can result in removing support from buildings or other configurations, culminating in catastrophic dropping. Soil cracks may also occur. These fissures may allow water to penetrate deeply when rainy conditions or runoff dominate.

This constant cycle of shrinking and expanding destroys tissues, and the damage intensifies over time. As a result, it is critical to stabilising the expanding soil with suitable inputs [70]. Some soils exhibit delayed volume changes without regard to loads and are produced by tumefaction or shrinking when water content varies [71]. In low-rise buildings with insufficient weight to support them, these volume changes can cause ground movement, causing them to collapse [72,73].

Shrinkage settlement of clay embankments during road construction can cause cracking and disintegrating highways supported by such soils. In areas with alternating wet and dry seasons, surfaces covered with expansive clay have visible construction damage [74]. Montmorillonite, a clay mineral that expands, is the reason of " expansive soils ". The primary content of moisture, void ratio, vertical tension, and the amount and kind of clay minerals all influence the volume change potential of soil [75]. Deformation resistance is excellent in cemented or undisturbed " expansive soil ". As a result, remoulded "expansive soil" expands greater than undisturbed soils.

4.2. Dispersive Soils

Clay particles deflocculate when repulsive interactions overcome attractive interactions, causing the particles to reject one another and form colloidal suspensions in the presence of reasonably clean water [76]. Below a certain velocity, running water causes no erosion in non-dispersive soil. Individual particles stick together and can only be eliminated using very corrosive water. Alternatively, no speed limit in soil is dispersive; even in still water, colloidal clay particles remain hanging, causing them further susceptible to drainage and erosion.

Clay fractions in dispersive and non-dispersive soils are not substantially different despite the high clay concentration in soils that dispersive, except for soils that possess particles of clay with less than 10%, which are likely devoid of adequate colloids to maintain pipe integrity. Dispersive soils can have up to 12% more dissolved salts in their pore water than ordinary soils. Soils with high amounts of salt cause particles of clay to agglomerate and cover silt and sand particles, causing the soil to flocculate [77]. Eroding dispersive soil has a mechanism that requires both the soil structure and the sort of interaction between the pore and eroding fluids.

The sort of the pH level, clay minerals exist, the organic matter, the temperature, the thixotropy, the water content, and the concentration and kind of ions in the pore and eroding fluids all affect the stress necessary to commence erosion. Swelling is caused by soil structure and osmotic pressures at the clay particles surface. This swelling reduces interparticle bonding forces and contributes to water erosion in cohesive soils. At the clay particle water contact, swelling is caused by concentration gradients as the soil system disperses. An eroding fluid's flocculated and deflocculated phases border are affected by its sodium adsorption ratio, concentration of salt, mineralogy, and pH value [78]. Filho observed, J.T. [110] that there was no considerable discrepancy between the control and those with the addition of "water treatment sludge" (WTS) for the water-dispersible clay mean values in the two soil samples investigated, and that pH was the factor was strongly linked to water-dispersible clay in both soils.

Experimental results, aiming at the beneficial reuse of waste and the preservation of natural geomaterials. According to a study by Boscov, M.E., et al. (2021) [110], the mineralogical tests show that Cubatão-WTS comprises quartz, goethite, muscovite, and kaolinite, mineralogically compatible with the gneissic rocks and residual soils through which the Cubatão River flows.

4.3. " Collapsible Soils "

Mosallaei, A., et al. (2022) [109] investigated that raising the proportion of "water treatment sludge" as an addition will boost soil cohesiveness and lower the internal friction angle ϕ. Due to volume loss being primarily triggered by moisture content increment, "Collapsible Soils" are moisture sensitive [71]. Specifically, wind-blown silts and loess can become unstable and collapse. Other materials may crumble, besides wind-deposited materials [79]. Large void ratios, porous textures, and low densities are common characteristics of "Collapsible Soils". Liquid limits usually have sufficient room to maintain saturation moisture levels during their normal state. These soils have good apparent strength at their typical low moisture content, but when wet, they are vulnerable to significant void ratio drops [80].

This means the metastable texture tumbles in wet soil because the links between the grains weaken. Soil particles must be rearranged into a denser packing state for collapse. On saturation, collapse often happens soon [81]. Sample testing is the most accurate method of determining collapsible soil [82]. However, an understanding of geology and geomorphology can aid in the prediction of collapsible soil deposits. The ability of soil to collapse may be assessed using liquid limit and dry density. The correlation between collapsibility, limit of liquid, and soil dry density is shown in Figure 2 [83].

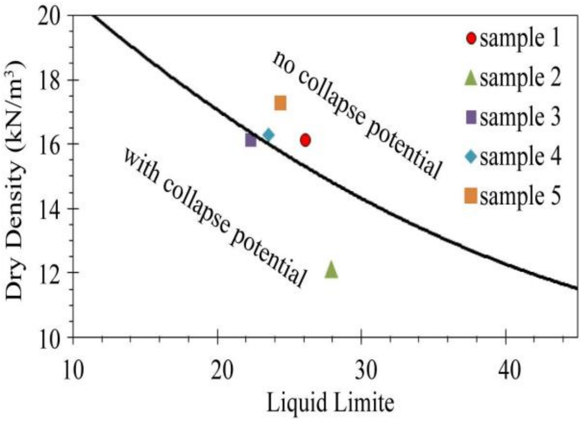


Figure 2. Collapse potential attention to liquid limit and dry density.

Geotechnical and geological engineers are aware of the possibility of some alluvial and wind-blown deposits in dry areas collapsing [84,85]. The WTS addition approach utilized in this research must be explained since most of the soils in case studies are collapsible. Using the collapsible test technique, an odometer was utilized in earlier investigations to assess an undisturbed material at its natural moisture content. The dial gauge is set to zero, and a 5 kPa is applied to the sample. A progressive rise in vertical stress is applied until the strain rate is less than 0.1% per hour. The stress is then raised until it surpasses the anticipated structural pressure or at least equals it. After flooding the sample, the resulting collapse strain is assessed [73]. Equation (2) [73] is used to determine the Collapsible index:

$$Ic= (H1 - H2)/H1 * 100 \qquad (2)$$

I_c: index of collapsibility

H1: The initial thickness of the soil sample (prior saturation).

H2: The final thickness of the soil sample (next saturation). Flooded compression curves are then generated based on the collapsed sample. A simple calculation of soil layer collapse is to multiply the layer thickness by the amount of collapse strain. Table 1 shows possible collapse severity [75].

In addition, the subgrade within cold periods, shifting water tables, and heavy traffic could encourage fine particle immigration from the subgrade to the sub base layers; Kermani et al. [88] researched this phenomenon and considered it to be a major contributor to pavement faulting and collapse. Road uplift (expansive soil) and floor slab uplift were explored by Tiwari et al. [89] as a cause of cracking floors and roadways. The "expansive soils" were to blame for this because they included minerals that make water absorb and expand in volume.

Table 1. The problematic soils as shown by Han (2015) [68] modified.

Refrence	Type of Soils	Problems	Results
Boscov, M.E., et al. (2021) [110],	Dispersive Soils	Accumulation Of High Levels of Sodium Ions (Na+) In the Soil.	the experimental investigation showed that soil: WTS mixtures are sound multipurpose geomaterials from a geomechanically point of view, considering permeability, shear strength, and deformability properties.
Al-Taie et al. (2019) [86].	Collapsible soils.	These problems are summarized, to include high erodibility, liquefaction potential, high settlement, ground heave or collapse, low bearing capacity, migration fine particles due to movement water table, etc.	Low contents up to 2% of waste materials are used as powder and ash in soil stabilization. Finally, in general, it was proved that the properties and behavior of modified soils change clearly with the application of different waste materials (from domestic and mining).
M. Chittaranjan, et. al. (2021) [87].	Expansive Soils.	Large volume changes (e.g., soil shrinkage, desiccation cracks and curling).	water treatment plant sludge or alum sludge can be a binding material due to its pozzolanic properties. Hence A study was made on the effects of variation of geotechnical properties of expansive soil treated with 2%, 4%, 6%,9% ,10% of water treatment plant sludge.

5. Heavy Metals

In "water treatment sludge," heavy metals from densely populated and industrialized regions, surface runoff, and domestic, commercial, and industrial sources are all present. As a result, they can accumulate on land when repeatedly applied with high concentrations of potentially toxic trace metals [103] and these substances pose a risk of entering the food chain [104] or causing phytotoxicity, which, if not handled safely, can be hazardous to human and environmental health [103, 105]. The following heavy metals are of concern to human health and the environment: nickel (Ni), cadmium (Cd), zinc (Zn), chromium (Cr), mercury (Hg), the trace metal cations lead (Pb), and copper (Cu) [106,105-95].

Metals with anionic traces such as arsenic (As), molybdenum (Mo), chromium (Cr), and selenium (Se) have gotten little attention while being identified as a priority "water treatment sludge" contaminant. Despite this, there are also notable differences between the two groups' soil chemical reactions, including alterations in the solubility of elements and soil adsorption with pH [107]. Information on the nature of the heavy metals (form, solubility, charge), as well as variables like organic matter content, pH, soil texture, structure of soil, and cation exchange capacity (CEC), is crucial to determining the fate and transport of heavy metals in sludge-amended soils, as well as their mobility, bioavailability, and ecotoxicity [105, 107, 96].

Most research investigations show varying and challenging-to-compare heavy metal concentrations in "water treatment sludge" (Table 2). However, the observed variations can also be attributed to the analytical goal of wastewater treatment plant design, which is to prevent oxygen depletion and eutrophication in surface waters. The heavy metal concentration in "water treatment sludge" directly relates to its source (industrial and domestic wastewater) and the sludge pre- and post-treatment processes used. This suggests that their primary goal is to clean the water component rather than effectively treat sludge. Urbanization and industrialization increase the wastewater produced in emerging markets and developed countries. Surface water contamination rises if the water is not properly cleansed, and more "water treatment sludge" is produced if it is not. Moreover, organic waste and chemical residues that could be phytotoxic or harmful to humans or animals, sewer sludge will also comprise microbiological pollutants (viruses, pathogenic bacteria, and protozoa besides other parasitic helminths).

Table 2. Numerous sludges' heavy metal content ($mg\ kg^{-1}$ DM).

Country	Cd	Cr	Cu	Hg	Ni	Pb	Zn	References
Canada	2.3–10	66–2,021	180–2,300		37–179	26–465	354–640	[90,91]
China	5.9–13	46–78	131–395	17–24	49.3–95.5	58–109	783.4–3,096	[92]
Egypt	0.9–312	89–993	83–2,640	0.1–16	5–645	50–1,724	112–6,298	[93]
Germany	0.8–16.6	16–66	168–228	0.65–2.5	24–39	34–49	674–827	[94]
India	41–54	102–8,110	280–543		192–293	91–129	870–1,510	[95,96]
Spain	1.0–3.0	122–244	275–331	1.5–1.7	32–64	71–105	500–880	[97]
Spain	1.0–2.0	163–318	200–575	1.0–2.0	55–152	70–167	540–2,100	[98]
Thailand	4.8	264	3,043		298	175.2	1,908	[99]
Turkey	1.3	321	388		128	29.2	541	[100]
UK	3.5	159.5	562		58.5	221.5	778	[101]
USA	25	178	616		71	170	1,285	[102]
Iraq	-	-	2500		-	520	740	[1]

The safe management of "water treatment sludge" in an economically feasible and ecologically acceptable manner provides a significant challenge to wastewater authorities because of the tightening regulations on sludge disposal. "Water treatment sludge" contains considerable amounts of useful substances, including organic matter, nitrogen, and phosphorus that must be reutilized in addition to certain potentially detrimental components. However, the negative effects of potential contaminants in sludge concern several interested parties. Several treatment options and disposal routes are investigated according to their sustainability and efficiency to achieve this objective. The research emphasizes that sludge management must be focused on optimizing future sustainability and useful reuse, and treatment technology must be affordable and effective.

6. Summary and Conclusion

Sludge combines particles and water pumped from lagoons used for wastewater treatment. It has the properties of a liquid or slurry and generally contains 2 to 15% oven-dried solids. Biosolids are dried sludge that resembles oven-dried solids and usually comprises between 50 and 70 per cent of the weight of bulk solids. The reprocessing and reclaiming of biosolids have significantly gained pace toward a more sustainable society due to the rise in the volume of wastewater biosolids generated annually worldwide and the growing need for virgin material. With a further yearly production of 66,700 tons, Iraq presently has more than 2 million tons of biosolids in depots or lagoons. This study demonstrates that in terms of geomechanical characteristics like permeability, shear strength, and deformability, soil: WTS blends are not appropriate as multifunctional geomaterials. According to preliminary environmental tests, they are also ecologically viable, although further research is needed to draw firm conclusions. Tests for leaching, simulating actual conditions for every usage, and tackling other pollutants, including bacteria, drugs, and hormones are all part of future study plans. Rock powder: WTS and lime: WTS combinations might be used in low-soliciting stress circumstances. However, low sludge concentrations were required to achieve the minimum shear strength for earthworks, indicating that the search for additives that can create acceptable all-purpose geomaterials must go on.

Moreover, the paper emphasizes the importance of defining WTS features in rheological and geological terms, and assessing whether they can be used sustainably in developing countries at most stages, from mingling and transport to environmental licensing. In general, WTS can be considered an effective material for improving the geotechnical properties of soils, such as the shear strength, especially when used with other additives such as lime. It was also noted from the results of previous studies that the expansive soils are more affected by the addition of WTS than the rest of the soils.

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